S
625.8
T6FHM
2005

FROST HEAVE OF A MONTANA SILT TREATED WITH REDUCED CEMENT CONTENTS

By

Russell D. Lay, E.I.T.
Graduate Research Assistant
Department of Civil and Environmental Engineering
Brigham Young University
Provo, UT 84606

and

W. Spencer Guthrie, P.h.D.
Assistant Professor
Department of Civil and Environmental Engineering
Brigham Young University
Provo, UT 84606

November 2005

Montana State Library
3 0864 1003 6662 7

FROST HEAVE OF A MONTANA SILT TREATED WITH REDUCED CEMENT CONTENTS

By

Russell D. Lay, E.I.T.
Graduate Research Assistant
Department of Civil and Environmental Engineering
Brigham Young University
Provo, UT 84606

and

W. Spencer Guthrie, P.h.D.
Assistant Professor
Department of Civil and Environmental Engineering
Brigham Young University
Provo, UT 84606

November 2005

ABSTRACT

A highly frost-susceptible soil was obtained from the Montana Department of Transportation and subjected to a regimen of tests at the Brigham Young University (BYU) Highway Materials Laboratory. The purpose of this testing was to evaluate the efficacy of Portland cement treatment for reducing the frost susceptibility of a Montana silt.

The research results indicate that a threshold cement content exists that provides adequate stabilization against frost heave. The use of a cement content greater than this value only marginally improves the heaving characteristics of the soil, while the addition of an amount less than this value will cause the treated soil to be more frost-susceptible than the untreated soil.

Digitized by the Internet Archive
in 2015

https://archive.org/details/frostheaveofmont2005layr

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Portland Cement Association (PCA) or the Montana Department of Transportation (MDT). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes.

ACKNOWLEDGMENTS

The authors wish to acknowledge David Luhr of PCA for funding this research and James Blossom and Susan Sillick of MDOT for providing testing material. In addition, the contributions of Brigham Young University (BYU) students Jon Hanson, Brandon Blankenagel, Ash Brown, Dane Cooley, Ben Griggs, and Ben Reese are appreciated. David Anderson of BYU provided invaluable assistance with the laboratory testing.

TABLE OF CONTENTS

Page

Chapter 1 Introduction 1

1.1 Problem Statement 1

1.2 Review of Previous Research 2

1.3 Outline of Report 3

Chapter 2 Background 4

2.1 Introduction to Frost Heave 4

2.2 Physical Motivations for Frost Heave 5

2.2.1 Heat Flow 5

2.2.2 Water Transport 7

2.2.3 Heaving Pressure 8

2.3 Frost Susceptibility 8

2.4 Typical Roadway Conditions 9

Chapter 3 Procedures 11

3.1 Soil Characterization 11

3.2 Soil Compaction and Strength 12

3.3 Moisture Susceptibility Testing 13

3.4 Frost Heave Testing 14

3.4.1 Specimen Preparation 14

3.4.2 Equipment Preparation 14

3.4.3 Temperature Settings and Data Collection 15

TABLE OF CONTENTS (Continued)

Page

Chapter 4 Results.....17

4.1 Soil Characterization.....17

4.2 Soil Compaction and Strength.....18

4.3 Moisture Susceptibility Testing.....20

4.4 Results of Frost Heave Testing.....21

Chapter 5 Conclusion.....28

5.1 Key Findings.....28

5.2 Recommendations.....28

Acknowledgements.....29

References.....30

CHAPTER 1
INTRODUCTION

A sample of highly frost susceptible soil was obtained from the Montana Department of Transportation. The soil has been used as a subgrade and was extracted from a borrow pit near Four Corners, Montana, along U.S. Highway 84 approximately 9 miles west of Bozeman, Montana. Figure 1.1 shows the exact location of the site. This soil was used in a study assessing the frost heave characteristics of soils treated with low levels of cement.

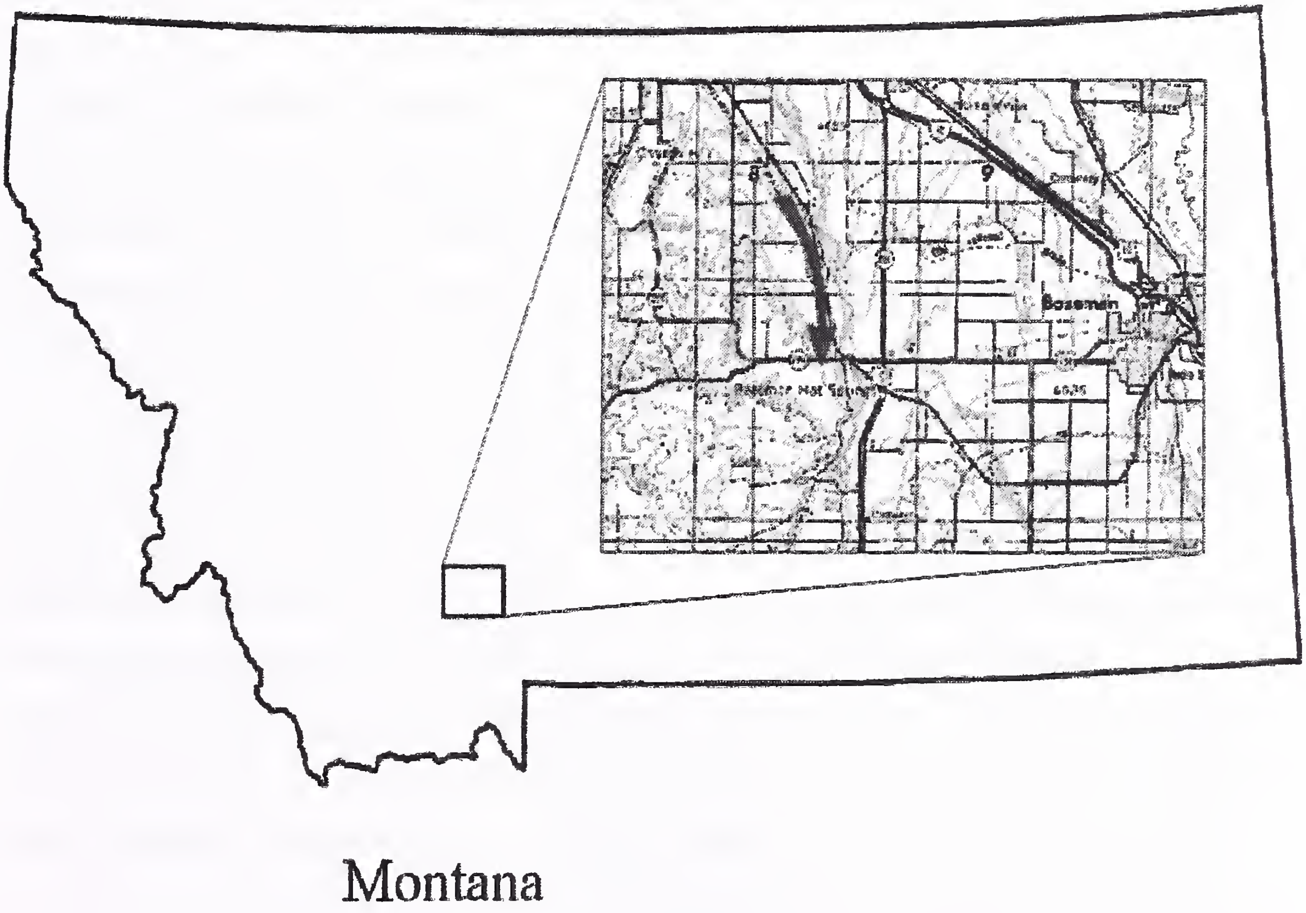


FIGURE 1.1 Soil origin.

1.1 Problem Statement

Government transportation engineers have estimated that over half of the costs associated with road maintenance in cold regions can be credited to the effects of freezing and thawing (*1*). One of the largest sources of this damage to roadways is frost heave and the

subsequent thaw-weakening of frost-susceptible pavement layers. As freezing temperatures penetrate frost-susceptible materials, significant amounts of water can be drawn up from underlying soil strata and freeze into layers of ice that usually form just above the freezing front. The expansion of this additional water as it freezes causes the road surface to heave upward. If the road surface heaves unevenly, stresses will develop in the pavement that can cause cracking and poor ride quality. Furthermore, when warmer weather induces thawing from the top down, the frozen soil beneath the thawing front can obstruct vertical drainage and cause supersaturated conditions to develop in the upper roadbed. The excess moisture dramatically reduces soil strength and increases the vulnerability of the pavement structure to damage under traffic loads.

1.2 Review of Previous Research

Research investigating the physical mechanisms that cause frost heave and measures that can be taken to mitigate frost damage have been carried out since the 1930s. Although much knowledge has been gathered, frost heave continues to cause significant problems throughout the cold regions of the world.

Methods of treating frost heave have traditionally focused on the removal of one or more of the three requisites for ice lensing (i.e. sustained freezing temperatures, a frost susceptible soil, and a supply of water). In cold climates the option of eliminating cold temperatures is typically uneconomical, however; eliminating freezing temperatures from roadways has been attempted by placing a layer of insulation into the roadbed (*2*). Treating a soil to reduce its propensity towards frost heave has been another option often utilized. In practice the most common form of frost heave prevention is to excavate the frost susceptible material and place in its stead a fill material that is not frost susceptible (*3*). Research has also been conducted on mixing selected coarse aggregates with a frost susceptible soil to reduce the frost susceptibility of the local soil (*4*). Research investigating methods to control water and its interaction with a freezing soil continues to be carried out as well. A wide range of chemical admixtures have been investigated. Chemicals such as ordinary as deicing salts, byproducts of paper mills, even products made from the toxic wastes of chemical plants have all been used (*5,6,7*). These chemicals are generally added with the intents of depressing the freezing temperature of

the soil water, decreasing the soil permeability, and repulsing water from the soil particle surfaces. Research concerning the insertion of geocomposites to cut off water flow within a soil has also been conducted (*1*).

Much research has been done on cementitious admixtures to soils as well. Lime and Portland cement have both been used with varying levels of success as an additive to frost susceptible soil (8, 9, 10, 11, 12, 13). Cement reduces the frost susceptibility of soils by reducing two of the requisites for ice lensing. First it develops strength to resist the heaving pressures created in a freezing soil, and second it also reduces the hydraulic conductivity of the soil (10). The use of cement as a stabilizing agent for marginal and poor materials has become common throughout north America. With the intent of giving a poor material even more strength cement contents of 8 percent and higher have commonly been added to soils. This higher cement content gives rise to a problem known as reflection cracking. As the cement in the treated soil hydrates, the soil contracts and transverse cracks develop which eventually propagate upward through the asphalt concrete pavement surface. In an effort to reduce reflection cracking lower cement contents are being tested on soils from across the United States. As a part of this research the effects of lower cement contents in soils are being tested with respect to the frost heave characteristics.

1.3 Outline of Report

This report contains five chapters. Chapter 1 presents the objectives of the research, and outlines the rest of the report. Chapter 2 describes the physical processes of frost heave, and discusses the effects of cement treatment to poor and marginal soils. Chapter 3 details the tests used to characterize the material, and the frost heave tests performed. Chapter 4 gives the results of the characterization tests and the frost heave testing conducted on the Montana silt treated with three levels of Portland cement. Finally, Chapter 5 presents a summary of the research findings and provides recommendations for further research.

CHAPTER 2
BACKGROUND

This Chapter explains the physical processes associated with frost heave, provides an overview of frost heave classification systems for soils, and briefly discusses the unique conditions that occur in frost-susceptible soils under a roadway.

2.1 Introduction to Frost Heave

Frost heave is the vertical displacement of the ground surface caused by the ingress and freezing of subsurface water within the underlying soil strata in response to the penetration of freezing temperatures into the ground. Frost heave occurs in seasonally frozen soils and is therefore associated with a cyclic process of freezing and thawing that can cause annual damage to affected roadways (*14*).

The two major components of frost heave are in-situ freezing and segregational frost heave. In-situ freezing results from in-place expansion of water as it freezes in the pore spaces between soil particles. When soil freezes quickly, in-situ freezing causes the majority of the heave (*15*). Although water expands approximately 9 percent in volume when it freezes, this type of frost heave is usually limited to less than about 3 percent of the depth of the frozen zone in unsaturated soils (*16*).

On the other hand, segregational frost heave, or ice lensing, has the potential to generate very significant frost heaves. For ice lensing to occur, three conditions must be met. First, sustained freezing temperatures must exist. Secondly, free water must be available, and, third, the soil must be frost-susceptible (*17*). Segregational frost heave occurs in freezing soil strata as frost penetration slows and a quasi-steady-state condition is developed. Water is drawn from the warmer, deeper soils toward the freezing front, where it eventually freezes. Ice lenses begin forming when the rate of heat removal approximately equals the rate of heat supply at the freezing front. The vertical displacement of the ground surface depends upon the cumulative thicknesses of the individual ice lenses. A more detailed discussion of the physical processes associated with frost heave is given in the next section.

2.2 Physical Motivations for Frost Heave

Frost heave results from complex relationships between heat flow, water flow, and stress distributions in freezing soils as discussed in the following sections.

2.2.1 Heat Flow

With the onset of freezing air temperatures above the ground surface, unsteady heat flow from the warm soil surface to the cold air is initiated. As increasing amounts of heat are removed from the soil, the freezing front begins to progress downward through the soil strata. Because air temperatures can drop much faster than soil temperatures, a large temperature gradient can be created at the air-soil interface. Large temperature differences cause the frost front to move rapidly downward through the soil nearest the surface. This rapid progression contributes to frost heave by in-situ freezing of the pore water between soil particles. In such cases of rapid freezing, no significant accumulation of water occurs, and the only heaving that occurs is due to the 9 percent increase in the volume of water as the liquid water changes to ice (*18*).

As soon as the frost front slows and a steady-state system is approximated, however, segregational frost heave becomes the major source of heave. Steady-state conditions occur when the energy extracted from the soil in the vicinity of the freezing front is equal to the energy provided by the underlying soil in the form of latent heat of crystallization released by the water as it freezes. At this time, further frost penetration ceases, and ice lensing occurs.

As long as a sufficient water supply is maintained and the thermal gradient remains constant, the ice lens can continue to grow almost indefinitely. However, the ability of the soil to supply water to the ice lens diminishes as the water in the region below the freezing front is exhausted. When the water supply to the growing ice lens becomes limited, the latent heat of crystallization may not equal the heat being removed from the soil, causing the frost front to continue downward until the conditions needed to form an ice lens are again met. In this way, a series of ice lenses form perpendicular to the direction of heat flow, separated by layers of frozen soil (*19*). As the ice lensing progresses downward, successive layers of lenses generally become thicker and more widely separated as shown in Figure 2.1.

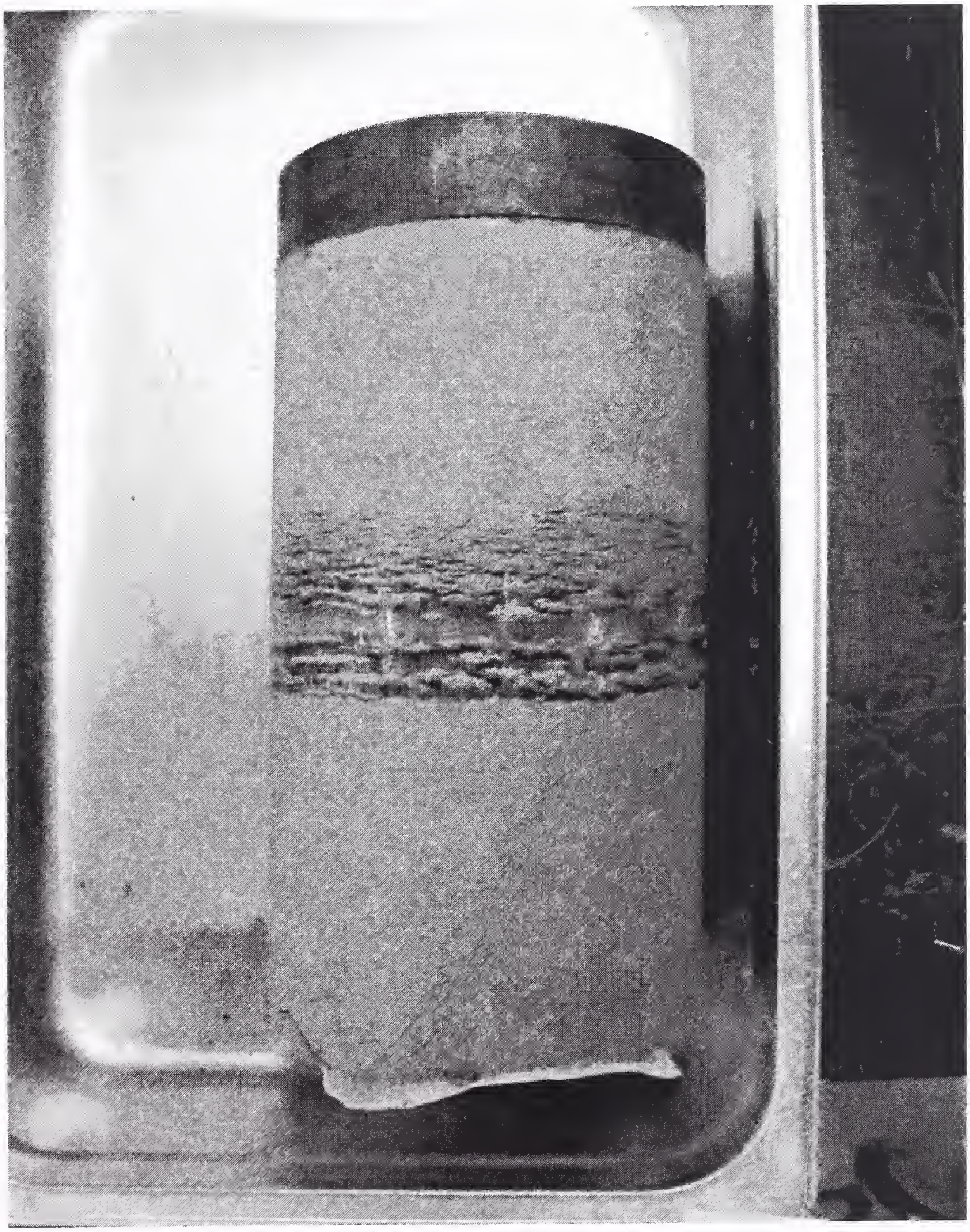


FIGURE 2.1 Ice lensing in a Montana silt.

2.2.2 Water Transport

The ability of water to move through the soil medium ultimately controls the growth of ice lenses in freezing soil. The transport of water from the warmer underlying soil towards the frost front is the result of three main mechanisms (*20*). First, the vapor pressure in warm, underlying soil is greater than in the cooler overlying soil; therefore, vapor flows toward the cold soil, where it condenses into liquid water and ultimately crystallizes into ice. The second mechanism of water transport is osmosis. As water crystallizes into ice at nucleation points within pore cavities, salts originally dissolved in the freezing water are expelled outwards into the adjacent, unfrozen water, thereby creating a region with higher ion concentrations and a depressed freezing temperature. In an effort to equalize ion concentrations with the pore water system, water migrates towards the frost front from below, where salt concentrations are lower.

The third and usually controlling mechanism is capillary rise, or water flow in response to matric suction gradients within the freezing soil profile. Before the soil begins to freeze, water on the surfaces of the soil particles and in the pore spaces between soil particles forms a network of channels through which water is able to flow. As the freezing front passes through the soil, ice crystals nucleate in the pore water between soil particles. The formation of ice in the pores causes the unfrozen water films on the surfaces of the particles to become thinner so that the effective radius of the capillaries forming the unfrozen water network within the freezing soil decreases. With decreasing temperatures, increasing amounts of pore water change to ice, further reducing the liquid water content between soil particles. Although the reduced water content causes a dramatic increase in capillary suction, the permeability of the soil rapidly diminishes as freezing progresses (*21*). Thus, as liquid water migrates from warmer to colder regions within the soil matrix, and especially as it approaches an active ice lens, its path becomes increasingly tortuous and narrow. At some point, the elevated matric suction levels are no longer able to overcome the reduced permeability, and water flow is terminated, usually at the base of the most recently formed ice lens.

Near the growing ice lens, unfrozen water exists only immediately around the soil particles and consists of adsorbed water molecules and saline water unable to be frozen. A schematic depicting the typical features of a freezing soil is shown in Figure 2.2.

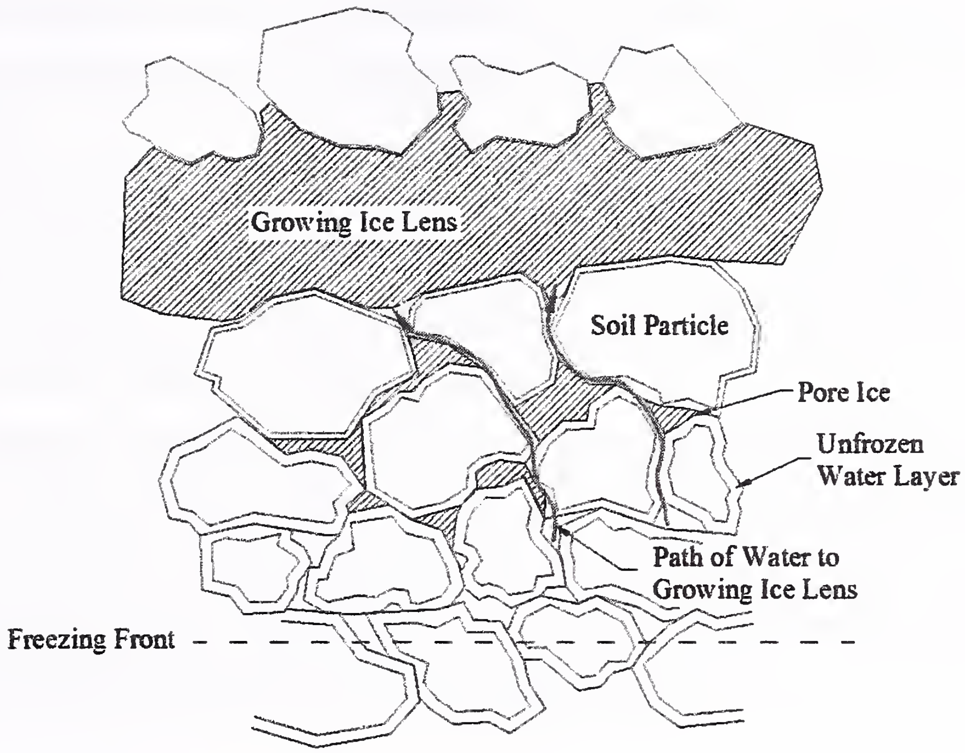


FIGURE 2.2 Schematic of a growing ice lens.

2.2.3 Heaving Pressure

As the pore ice grows to form an ice lens, particle-to-particle contact within the soil is disrupted. The weight of the overburden is subsequently transmitted from the soil matrix to the ice-water structure, leading to pressurization of the unfrozen water films along the soil-ice interfaces (*22*). Additional water can enter the film only when the suction at the interface is sufficient to overcome the counteracting overburden stresses. Because typical overburden pressures in a roadbed range from only 0.4 psi to 3.0 psi, and the pressure required to terminate heave in a silty soil is approximately 11.6 psi, frost heaving can readily occur in frost-susceptible soils given the presence of freezing temperatures and available moisture (*23*).

2.3 Frost Susceptibility of Soils

Several methods have been developed to determine if a soil is susceptible to ice lensing. According to Konrad, three levels of sophistication exist for estimating the frost susceptibility of a soil. Level-one methods are based on the percent of soil finer than a certain size, typically 0.003 in. or 0.0008 in. Level-two methods are based on particle-

size distributions and additional tests regarding the interaction of the soil and water. Level-three methods are based on actual frost heave tests, either in the laboratory or in the field (*24*).

The most widely used frost classification method is a level-one method developed by the United States Army Corps of Engineers (USACE) that is based largely on the work of Casagrande (*14*). This method classifies soils into four groups labeled F1 through F4, with F4 being the most frost-susceptible.

Clean sands and gravels are typically too well drained to draw water to a potential ice lens by capillary action, and clays conduct water too slowly to supply the needs of a growing ice lens (*20*). Thus, silts, which are fine enough to develop significant matric suction but still coarse enough to allow water to readily permeate the soil matrix, are generally considered to be the most frost-susceptible (*25*).

2.4 Typical Roadway Conditions

In order for the conditions experienced by subsurface soil layers comprising a pavement structure to be simulated, those conditions must be clearly understood. The differences between natural and laboratory conditions account for many of the unsatisfactory results obtained from laboratory experimentation (*26*).

Most pavement surface layers are underlain by an aggregate base course. The base course is typically a well-graded gravel with low fines content designed to provide both strength and lateral drainage. While such high-quality base materials are usually non-frost-susceptible, the absence of liquid water within the material allows the freezing front to rapidly penetrate the pavement structure into the subbase and subgrade, which may be frost-susceptible.

Based on computations performed using data collected in Sweden, the temperature gradient that spans from the frozen front to the bottom of the lowest ice lens in a typical soil column under a roadway is approximately 0.27°F/in. of soil depth (*27*). During winter in cold climates, however, the temperature conditions that occur immediately beneath a pavement can vary significantly from those present in the soil beyond the shoulders of the road. Because snow behaves as an insulation layer, plowing the snow from a road surface exposes the pavement to a larger thermal gradient than

would otherwise exist. The larger thermal gradient leads to colder temperatures and increased frost penetration compared to soils located beyond the pavement shoulders (*28*).

CHAPTER 3

PROCEDURES

This chapter describes the methods of soil characterization utilized in the research, strength and moisture susceptibility testing procedures, and the frost heave testing protocol used to assess the effects of cement stabilization on the frost susceptibility of the Montana silt.

3.1 Soil Characterization

The Montana silt was first classified using two principal methods, the Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) classification system. These methods are based on particle-size distributions and Atterberg limits, with the AASHTO method being the most common specification used in the United States for highway design.

Soil preparation began with drying at 140°F for 24 hours. After the soil was dried, it was sieved through various sieve sizes to facilitate construction of replicate specimens with identical gradations. A washed sieve analysis was performed according to ASTM D 2217 to determine the particle-size distribution of the soil over nine sieve sizes. A hydrometer test was also conducted according to ASTM D 422 to determine the particle-size distribution of the portion of the sample finer than 0.003 in. (*29*). Atterberg limits tests were performed according to ASTM D 4318 to determine the plastic and liquid limits of the soil, and the apparent specific gravity of the material was measured using ASTM D 854 (*29*).

The electrical conductivity of the soil was also assessed to give an indication of the salinity of the soil, which can have a direct impact on frost heave behavior. As both the freezing temperature of the soil water, and the magnitude of matric suction that develops upon freezing are dependent on salinity. For this test, 0.011 lb of air-dried soil was placed into a clean bottle with 0.220 lb of deionized water. The soil and water were thoroughly mixed, and a dual platinum-plate, contacting-type probe was used to measure the electrical conductivity of the solution. Measurements were taken at specified intervals until the electrical conductivity stabilized at a constant value.

3.2 Soil Compaction and Strength

As the Montana silt tested in this research was a highway subgrade soil, the standard Proctor compaction effort was utilized in specimen preparation. Each specimen was prepared by weighing out exact amounts of each particle size as determined by the dry sieve analysis that had been conducted previously. The optimum moisture content and maximum dry density were determined by compacting multiple specimens at various moisture contents. Data from the optimum moisture content analysis showed that this soil retains a gravimetric moisture content of approximately 2 percent in the air-dry condition. Thus, a correction in the amount of water needed for compaction at the optimum moisture content was applied during specimen preparation.

State highway departments commonly specify unconfined compressive strengths for cement-treated soils used in road construction. In this research, cement contents corresponding to 7-day unconfined compressive strengths of 200 psi, 400 psi, and 600 psi were selected for evaluation; these target values represent the typical range of values specified by highway agencies. The specimens were prepared with various amounts of cement and tested for strength according to ASTM D 1633 except that the specimens were not soaked before testing (29). In order to provide water for cement hydration while still maintaining sufficient moisture for compaction, an additional amount of water was added to the specimens that contained cement. The weight of the additional water was equal to 20 percent of the weight of the cement added. All samples were compacted using the standard Proctor compaction effort and allowed to cure for 7 days at 100 percent relative humidity. After curing, the specimens were capped with gypsum, and tested in a compression machine at a strain rate of 0.05 in. per minute. A floating head was used to ensure a uniform distribution of load across the specimen end caps. The maximum loads sustained during testing were utilized to compute the unconfined compressive strengths of the specimens, which were in turn employed to determine the target cement contents for use in the research.

3.3 Moisture Susceptibility Testing

In addition to strength testing, the moisture susceptibility of the soil was also assessed. Moisture susceptibility testing was performed using the Tube Suction Test (TST) as outlined in Texas Department of Transportation Test Method Tex-144-E. For the TST, three replicate specimens prepared at four different cement contents were compacted in plastic containers pre-drilled with 0.0625-in.-diameter holes in the bottom and allowed to cure at 100 percent relative humidity for 7 days.

After the curing period, the specimens were dried at 140°F for 72 hr. Once the drying process was complete, the specimens were placed in a 0.5-in.-deep bath and allowed to imbibe water over a 10-day soaking period. The surface dielectric values of the specimens were then measured daily during this period, with six readings per specimen taken at each time interval.

The dielectric value of a soil medium is most sensitive to the presence of unbound water, which plays a primary role in numerous pavement damage mechanisms. For materials with high suction and sufficient permeability, substantial amounts of unbound water rise within the aggregate matrix, leading to higher dielectric values at the surface. Non-moisture-susceptible materials, on the other hand, maintain a strong moisture gradient throughout the test, with little moisture reaching the surface, and have lower dielectric values at the end of the TST.

The interpretation of TST results is based on an empirical relationship between the final dielectric value and the expected performance of aggregate base materials (*30*). Aggregates whose final dielectric values in the TST are less than 10 are expected to provide superior performance, while those with dielectric values above 16 are expected to provide poor performance as base materials. Aggregates having final dielectric values between 10 and 16 are expected to be marginally moisture susceptible. Laboratory tests have confirmed a positive correlation between the TST moisture susceptibility classifications and the strength loss and frost heave characteristics of pavement base materials (*31, 32, 33*).

3.4 Frost Heave Testing

Once the soil characteristics were established, frost heave testing commenced. This section describes the procedures used to prepare the specimens for frost heave testing, as well as the protocol followed for temperature settings and data collection.

3.4.1 Specimen Preparation

Each frost heave specimen was prepared using proportions representative of the different particle sizes calculated from the dry sieve analysis initially conducted on the material and compacted into cylindrical molds pre-drilled with seven 0.125-in. diameter holes in the bottom to allow for water uptake. A filter paper was placed in the bottom of the mold prior to compaction in order to prevent the ejection of fines into the bath water during frost heave testing. The weight of the mold and specimen was measured just after compaction, and four height measurements were taken to determine the initial height of each finished specimen. The specimens were then cured at 100 percent relative humidity for 28 days and weighed again (*9*).

3.4.2 Equipment Preparation

Seven thermocouples were inserted into three specimens at 1-in. intervals beginning at the soil surface and extending down the sides of the specimens to a height of 3 in. from the specimen base. An example of a specimen instrumented with thermocouples is shown in Figure 4.2.

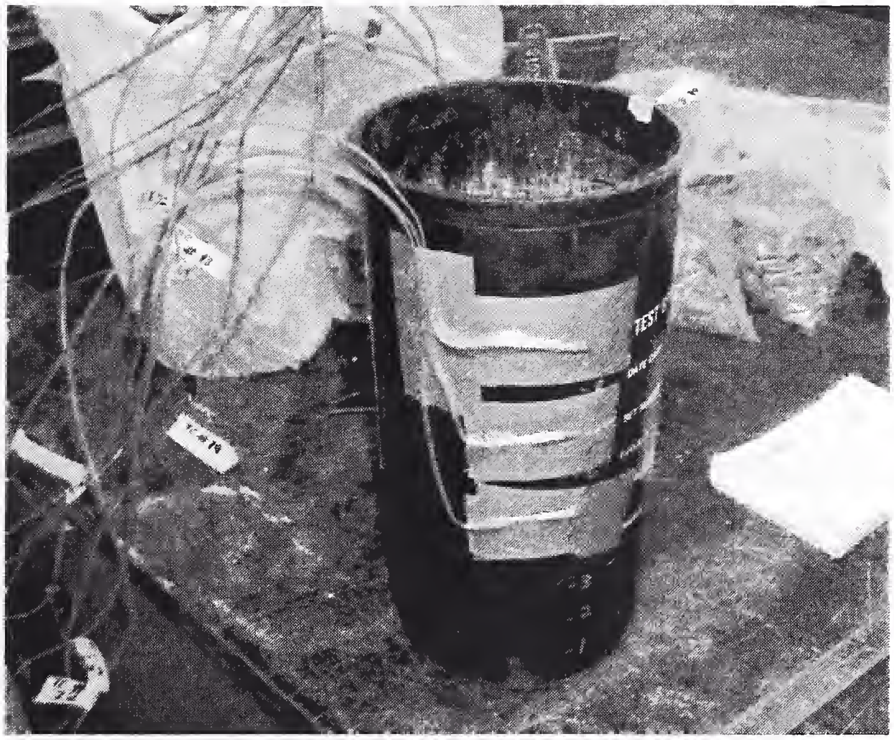


FIGURE 4.2 Specimen instrumented with thermocouples.

After the specimens were instrumented, they were wrapped with lateral insulation. In each case, the insulation extended above the top of the mold, and downward along the length of the specimen. After the specimen was instrumented and the insulation was in place, overburden weights were then placed onto each specimen. During frost heave testing the height of the water table was set between 1.75 in. and 2.0 in. deep. Prior to the start of the test, an LVDT was centered on top of each specimen to measure the axial change in length.

3.4.3 Temperature Settings and Data Collection

Frost heave testing was conducted with the environmental chamber air temperature at 19.4°F, and the water temperature at 36.5°F. Both the temperature profiles and the changes in length were automatically recorded on 10-minute intervals throughout the duration of the 10 day test using a computerized data acquisition system.

Directly after the frost heave test, the excess water was wiped off the specimen, the insulation and instrumentation were removed, and the weight of the specimen, mold, and overburden weight was measured. The overburden weights were not removed because they were still frozen to the specimens.

Following the weight measurements, six of the twelve specimens tested, were removed from their molds before significant thawing could commence, and the frozen specimens were closely examined. The height of the lowest ice lens was recorded together with the lengths of the area with lenses and the area without lenses. The final total length was also measured on the specimens removed from the molds, so that a comparison could be made between the length measured by the LVDT and the observed length.

After the ice lensing observations were documented, the specimens were placed in an oven at 230°F. After the specimens were fully dried the weight of the oven dry specimen was taken.

CHAPTER 4

RESULTS

This chapter presents the results of the soil characterization, strength and moisture susceptibility, and frost heave tests conducted on the Montana silt. The majority of this chapter gives a detailed report of the results obtained by frost heave testing.

4.1 Soil Characterization

Tests conducted to classify the soil and to determine its physical characteristics included a washed sieve analysis, a hydrometer analysis, Atterberg limit tests, a specific gravity test, and an electrical conductivity test. The Montana silt had liquid and plastic limits of 25.80, and 25.79 percent, respectively. These results indicate that the soil is non-plastic. The apparent specific gravity of the soil was found to be 2.67. The grain-size distribution is shown in Figure 4.3. As discussed in Chapter 2, certain grain-size distributions are associated with greater frost susceptibility than others. According to this particle-size distribution and the measured Atterberg limits, this soil is classified as an A-4 (0) material in the AASHTO classification method and as ML, which is silt with sand, in the USCS. According to the frost susceptibility classification system developed by the United States Army Corps of Engineers, this soil meets the requirements for an F-4 rating, the most frost-susceptible classification possible.

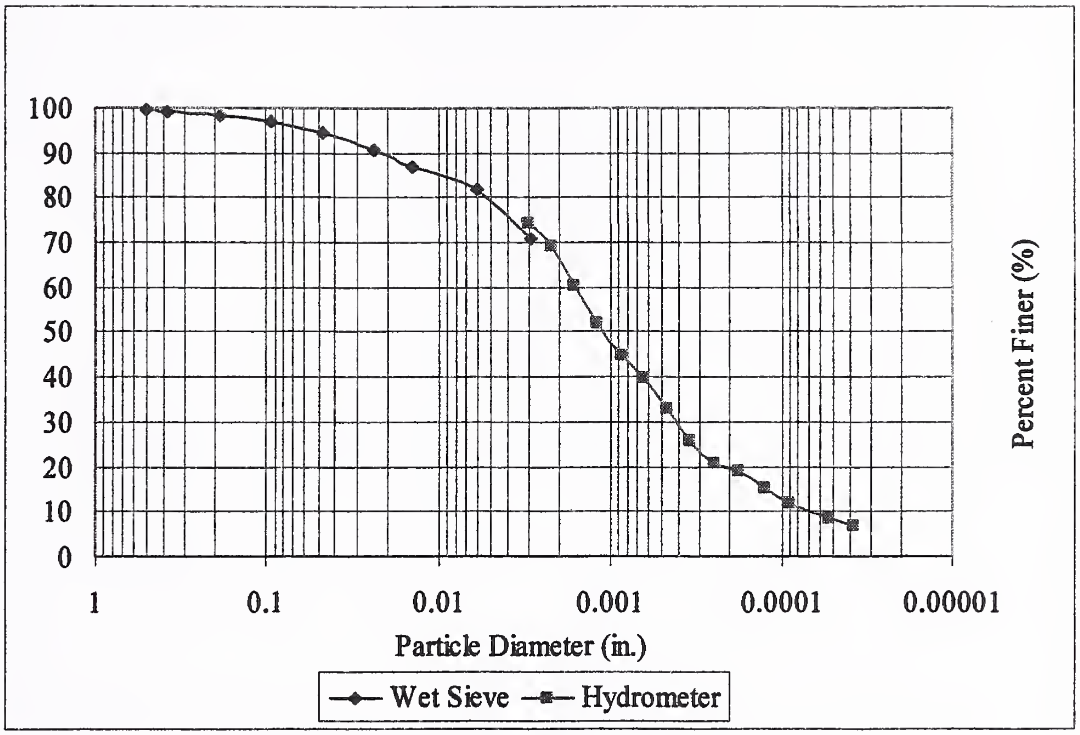


FIGURE 4.3 Soil particle-size distribution.

The electrical conductivity of the soil is an indicator of the amount of salts in the soil, which can affect the formation of ice lenses as discussed in Chapter 2. After 26 days of testing, the electrical conductivity readings stabilized at approximately 432 micro-Siemens per in. This comparatively low salt concentration was expected, as the soil was obtained from a borrow pit and had never been exposed to deicing salts.

4.2 Soil Compaction and Strength

Three additional tests were conducted to investigate the strength and behavior of the material. First, a moisture-density curve was established as shown in Figure 4.4. This curve indicates that the optimum moisture content is 20 percent and the maximum dry density is 101 lb/ft^3 when using the standard Proctor method of compaction.

The unconfined compressive strength test revealed that the desired compressive strengths of 200 psi, 400 psi, and 600 psi were approximately obtained when the soil was mixed with, 2.0, 3.5, and 5.0 percent cement, respectively. Figure 4.5 shows the compressive strengths of the samples tested at various cement contents.

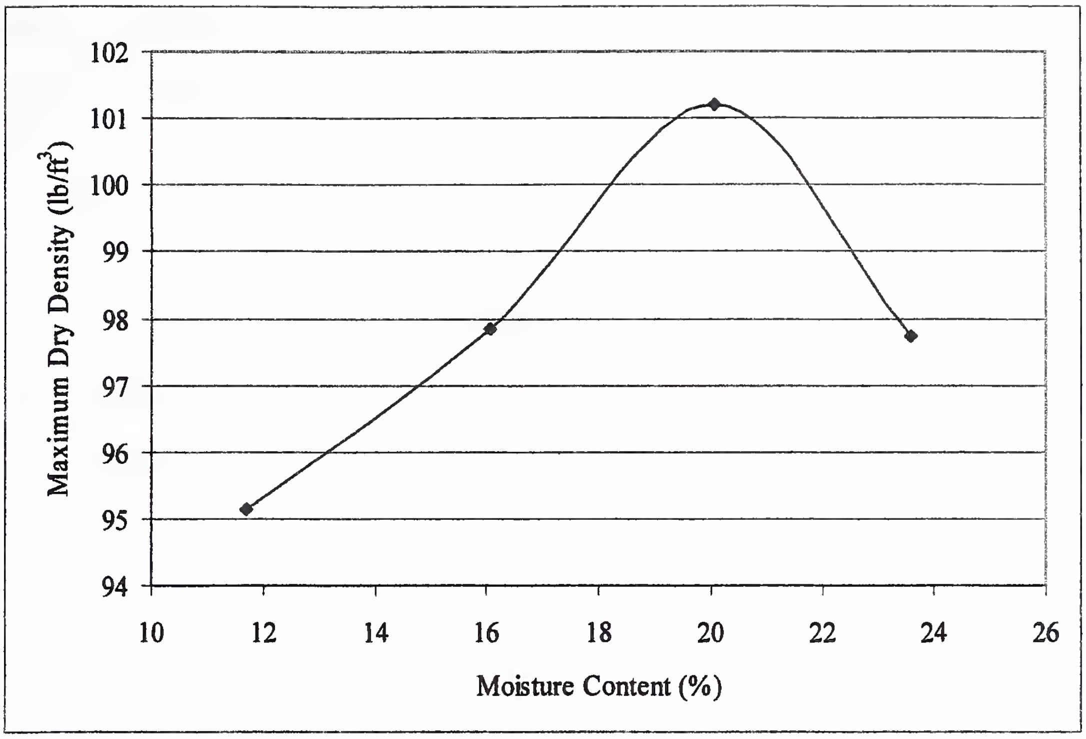


FIGURE 4.4 Moisture-density curve.

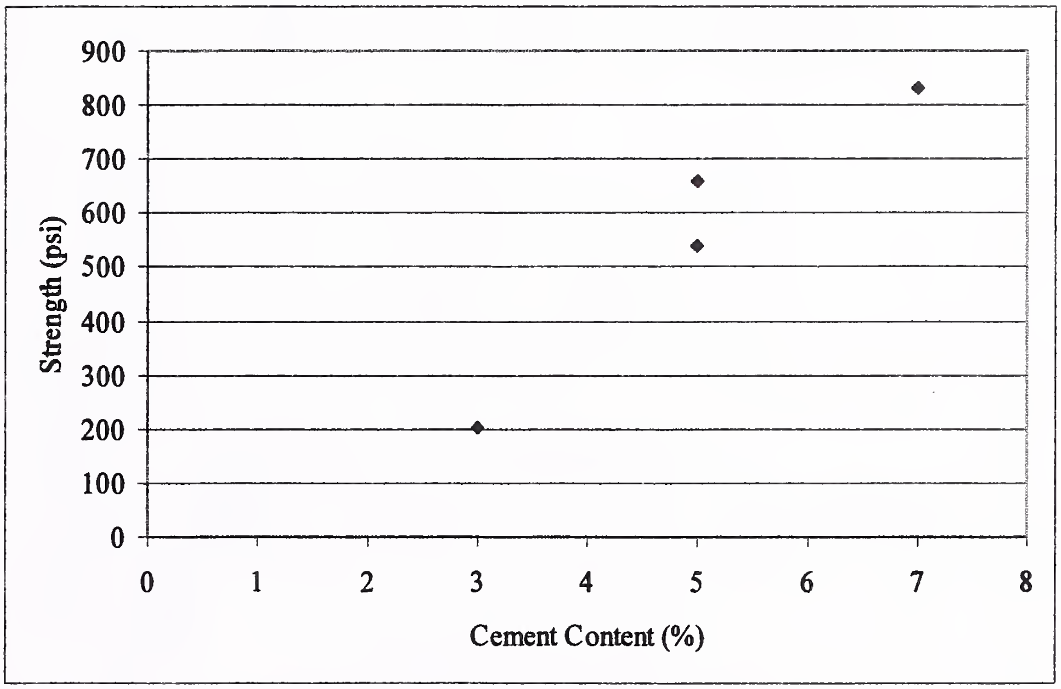


FIGURE 4.5 Effect of cement content on strength.

4.3 Moisture Susceptibility Testing

The TST was conducted in an effort to correlate dielectric measurements to frost susceptibility. The average dielectric values at the end of the TST are shown in Table 4.1 together with the corresponding level of moisture susceptibility. The dielectric values plotted over time are shown in Figure 4.6.

According to the moisture susceptibility ratings resulting from the TST, all specimens have the potential for frost heave, as of the final dielectric values exceed 10. The TST also indicates that increased cement content decreases the moisture susceptibility of the soil.

TABLE 4.1 Tube Suction Test Results

Cement Content (%)	Average Final Dielectric Value	Moisture Susceptibility Rating
0.0	21.9	Poor
2.0	15.8	Marginal
3.5	14.2	Marginal
5.0	11.2	Marginal

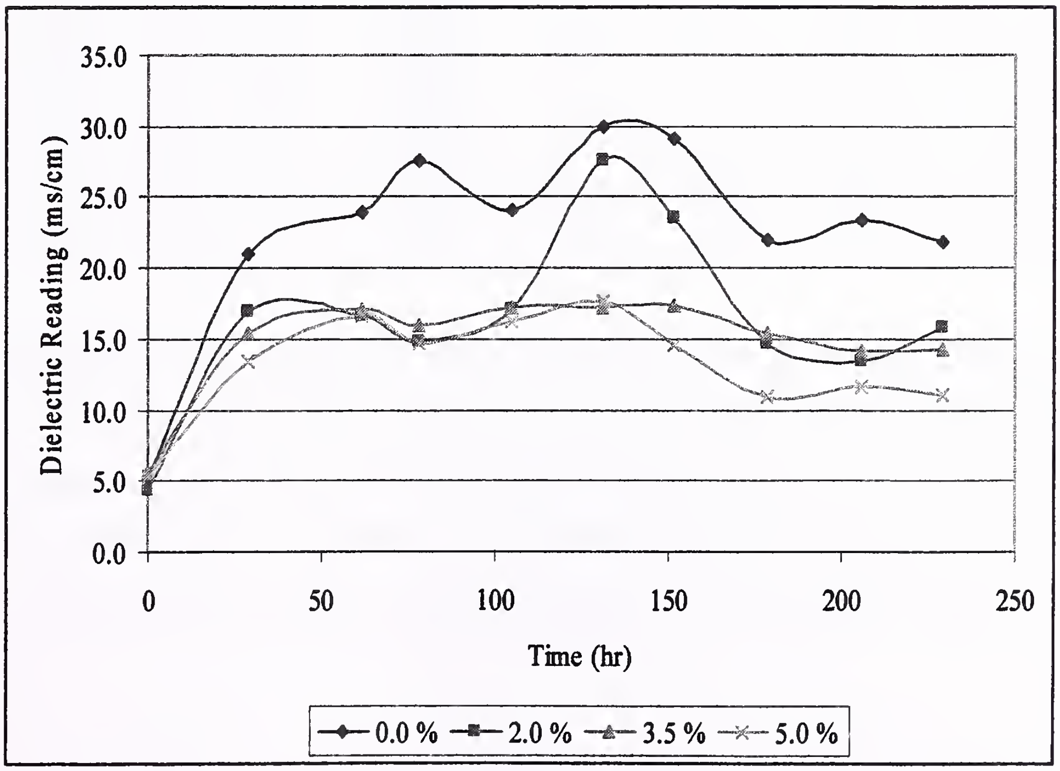


FIGURE 4.6 Average dielectric readings.

4.4 Results of Frost Heave Tests

This section analyzes the effects of varying cement contents on the Montana silt. Four different groups with three specimens per group, were tested. The groups were designed to have cement contents of 0.0, 2.0, 3.5, and 5.0 percent, and were tested in the BYU frost heave testing apparatus. Table 4.2 shows data collected from the 12 frost heave samples. The analysis that follows is based mainly on this information and the temperature data that were collected during the test.

TABLE 4.2 Frost Heave Test Data

Cement Content (%)	Moisture Content at Compaction (%)	Dry Density at Compaction (lb/ft^2)	Initial Length (in.)	Length Change durring Test (in.)	Weight Gain durring Test (lb)	Moisture Content at End of Test (%)
0.0	20.5	106.7	8.57	1.18	1.02	30.0
0.0	19.8	106.8	8.65	1.17	1.02	29.5
0.0	20.2	106.9	8.57	1.21	1.25	29.8
2.0	19.8	101.3	9.27	1.50	1.45	34.6
2.0	19.8	101.8	9.22	1.25	1.77	33.0
2.0	20.1	101.5	8.96	1.34	1.62	34.0
3.5	19.0	100.6	9.32	-0.04	0.92	25.9
3.5	19.4	99.8	9.59	0.06	1.11	27.1
3.5	18.9	100.5	9.30	-0.04	0.66	25.8
5.0	19.1	100.6	9.04	-0.04	0.78	25.4
5.0	17.9	100.2	9.38	-0.03	1.04	25.2
5.0	19.1	100.3	9.08	-0.03	0.60	25.8

Figures 4.7, 4.8, and 4.9 show relationships between the cement content, water uptake, and frost heave exhibited. Figure 4.9 shows that during testing the moisture content of specimens treated with 2.0 percent cement increased 14 percent over the optimum moisture content. The bar in the figures represents the average value, while the upper and lower ends of the lines denote the high and low data points, respectively.

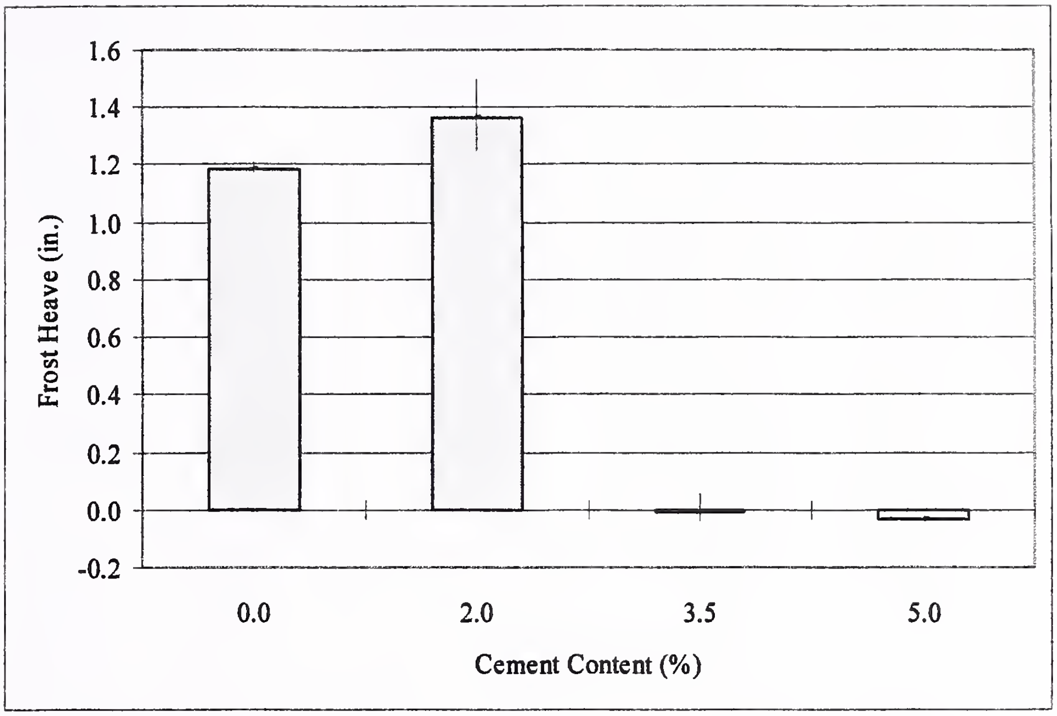


FIGURE 4.7 Frost heave at end of 10-day test.

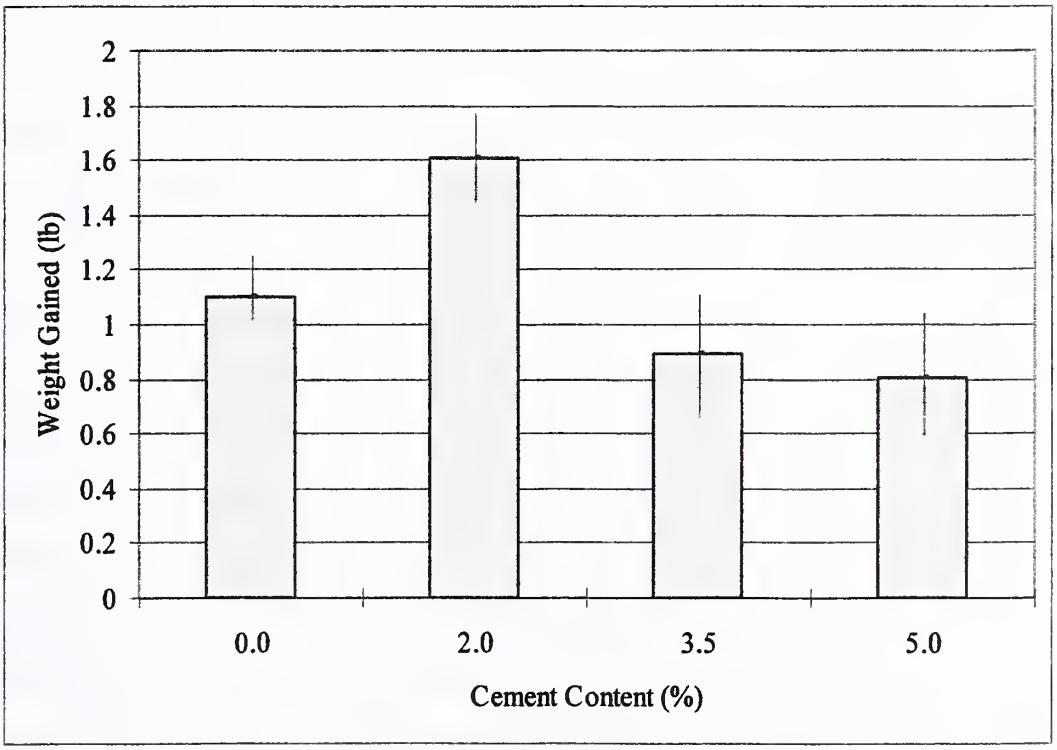


FIGURE 4.8 Weight gained by end of 10-day frost heave test.

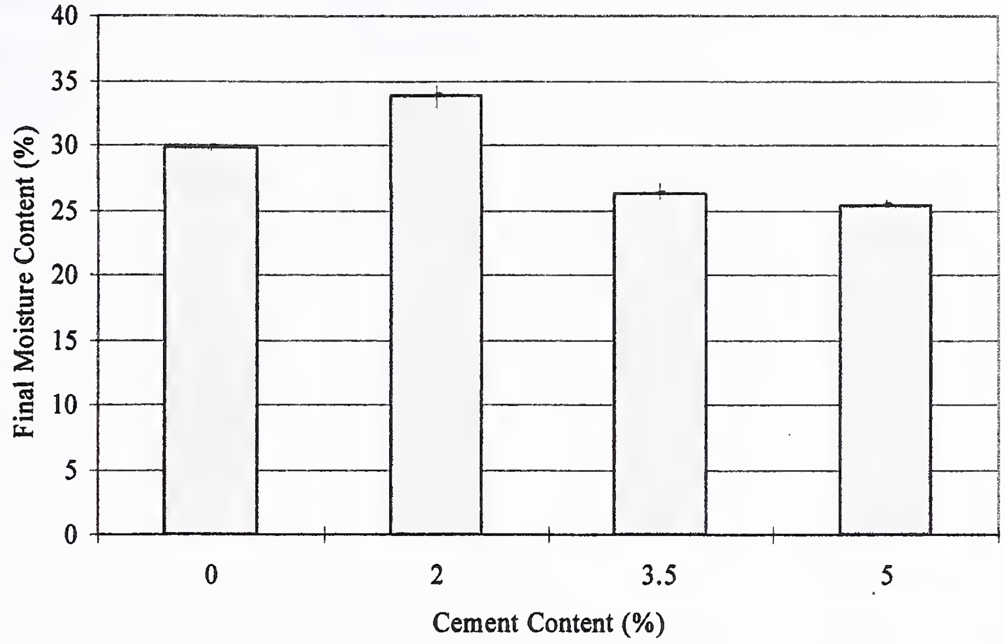


FIGURE 4.9 Moisture content at end of ten day test.

The treatment of a silty subgrade soil with cement proved to be effective in controlling frost heave when a sufficient amount of cement was added; however, when an insufficient amount of cement was applied, the frost heave exhibited was actually greater than that seen in untreated samples. This behavior is likely caused by an increase in matric suction, but an insufficient reduction in permeability, associated with the addition of 2 percent cement. Furthermore, treatment with just 2 percent cement apparently did not develop the strength necessary to resist the heaving pressures that occurred in this material during freezing. The data collected for specimens treated with 3.5 percent and 5.0 percent cement suggest that once a sufficient amount of cement required to prevent frost heave is reached, the addition of more cement only marginally increases resistance to frost heave. The slight decrease in length exhibited by the specimens with 3.5, and 5.0 percent cement was likely caused by thermal contraction as the specimens cooled.

The specimens with 5.0 percent cement imbibed 73 percent as much water as did the untreated control specimens and yet exhibited negative heave; whereas the control group heaved an average of 1.19 in. This result shows that although the cement treatment is totally effective in eliminating frost heave, it is only marginally able to reduce water

flow into the soil. This observation is consistent with the marginal moisture susceptibility rating received by these specimens in the TST.

Temperatures were measured throughout the duration of the tests using thermocouples as described previously. Figure 4.9 shows the typical temperature profile of a specimen throughout the duration of the test. The coldest temperature occurs at the surface and increases at a constant rate with increasing specimen depth. The temperature difference between the top and bottom of the specimens was 10.80°F, which corresponds to a thermal gradient of 1.20°F/in.

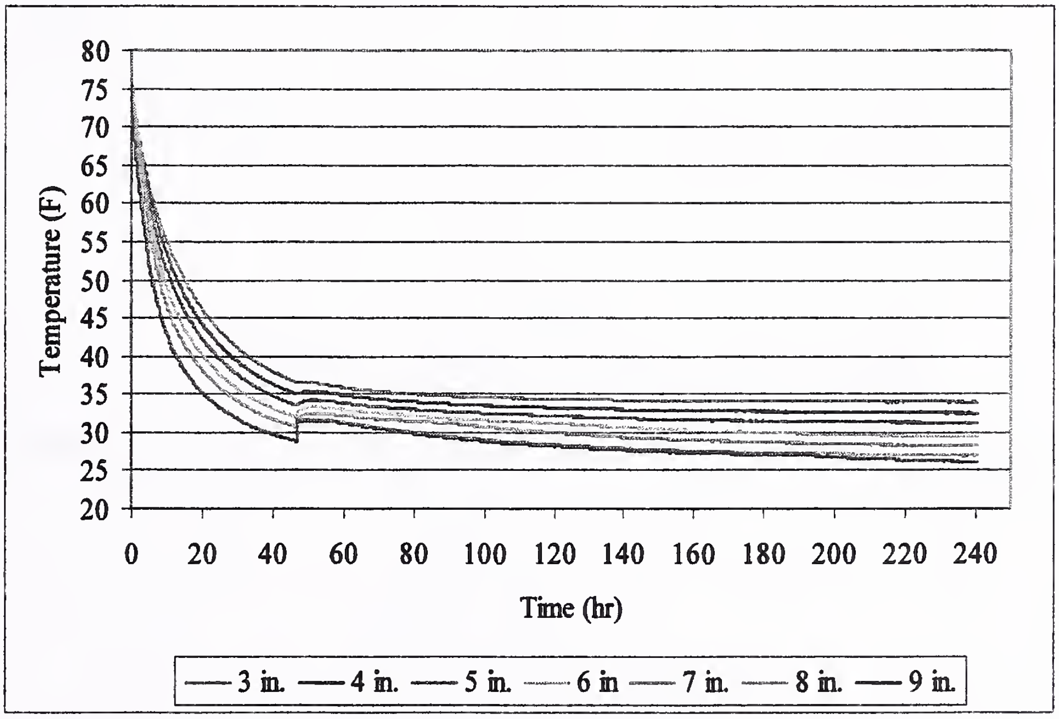


FIGURE 4.9 Temperature readings at various heights within a specimen.

The air and water temperatures were also monitored throughout the test. Thermal equilibrium was reached at a time of approximately 100 hours from the beginning of the frost heave test. Analysis of the water temperatures after 100 hours showed the mean water temperature to be 36.36 ± 0.28°F and the air temperature to be 18.91 ± 1.74°F. Figures 4.9 and 4.10 suggest that the minor fluctuations of the air temperature had no visible impact on the temperatures of the specimens or the water, however.

The data collected by the LVDTs also provided valuable information about the frost heave characteristics of the soil. Figure 4.12 shows a graph of the axial elongation of four specimens representative of each cement treatment level.

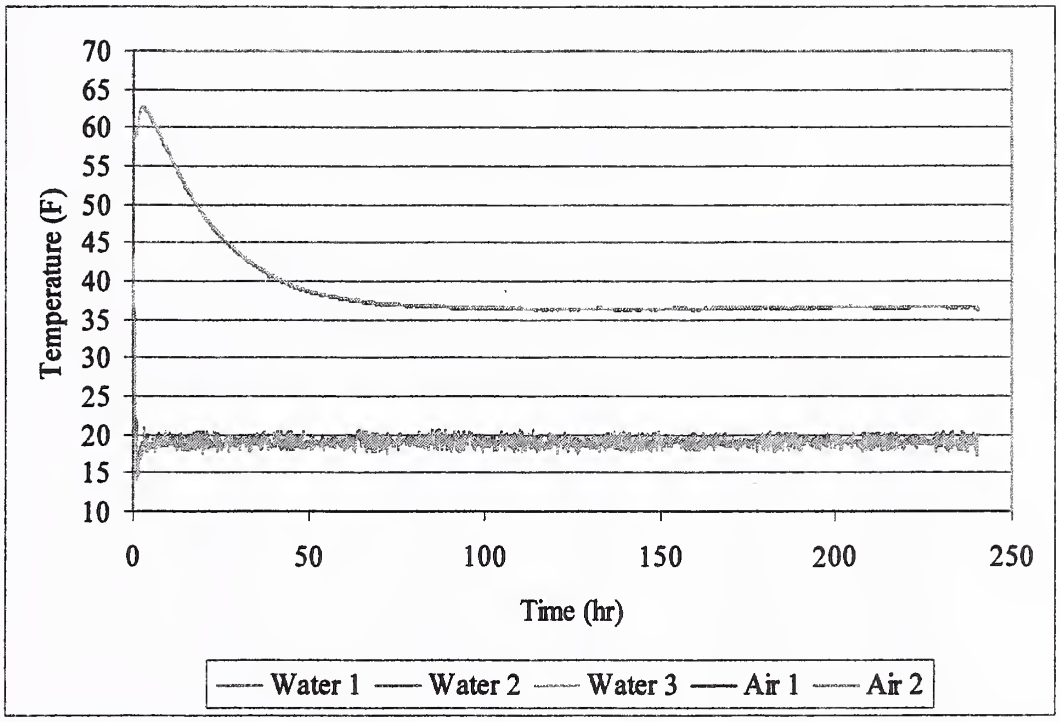


FIGURE 4.10 Typical temperatures for air and water during testing.

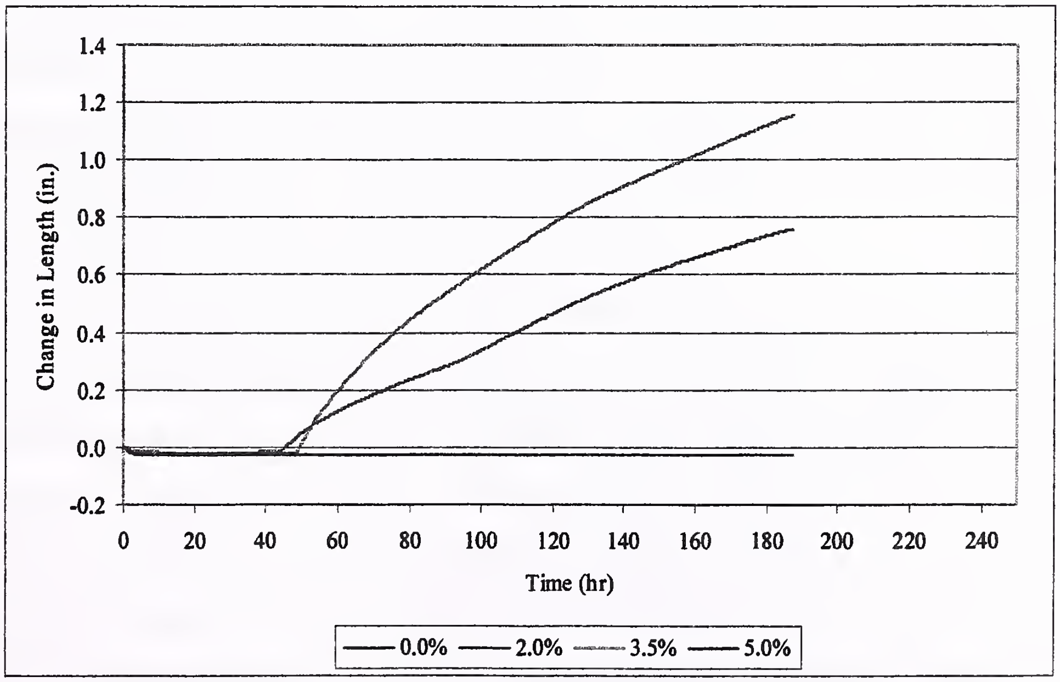


FIGURE 4.11 Representative frost heave of specimens during testing.

Although thermal equilibrium was reached at approximately 100 hours into the test, a constant frost heave rate was not reached until approximately 134 hours into the test. From this time forward, the heave rate remained approximately constant throughout the remainder of the test. The rate of heave between 134 and 240 hours, which was the end of the test, was chosen as the time period used to calculate the average frost heave rate. Table 4.3 shows both the total amount of heave and the average heave rates experienced by the specimens as a function of cement content.

TABLE 4.3 Total Heave and Heave Rate

Cement Content (%)	Frost Heave (in.)		Heave Rate (in./day)	
	Average	Std. Dev.	Average	Std. Dev.
0.0	1.19	0.02	0.14	0.01
2.0	1.36	0.13	0.14	0.01
3.5	-0.01	0.06	0.00	0.00
5.0	-0.03	0.01	0.00	0.00

As displayed in Figure 4.9, a sudden rise in temperature occurred in all specimens typically between 36 and 49 hours into the test. The sudden rise in temperature preceded the start of heaving in all cases by an average of 38 minutes for the specimens that exhibited heave. Although all specimens experienced the increase in temperature, only the untreated specimens and those treated with 2.0 percent cement heaved. At the point of heave initiation, the heave rate increased within a 10-minute period from a negative heave to the highest rate experienced by the specimen.

The point of heave initiation can be explained in the following way. Ice lensing cannot occur exactly at the freezing front in most soil media due to a depression in the freezing temperature of the soil water associated with salinity and matric suction effects (*34*). Once the freezing front has penetrated sufficiently into the soil, the pore water near the surface will change to ice. The sudden lack of liquid water near the soil surface dramatically increases the matric suction of the specimen in the vicinity of the ice. In response, pore water originally located lower in the specimen or in the water bath rises into the specimen through capillary rise, which causes the temperature of the soil near the

point of water arrival to increase; the increase was measured to be 2.9°F on average in the testing conducted in this research. This warming is due to the energy contained in the water arriving from lower, unfrozen soil. Only after the arrival of this wave of water does ice lensing begin to occur. The initial heave rate then slows to a constant, sustainable rate as the liquid water from the initial wave and the existing pore water is depleted and the rate of water migration to the growing ice lens from lower in the soil specimen reaches a steady state.

Figure 4.13 shows a close-up view of the typical changes in length through time experienced by samples with 3.5 and 5.0 percent cement. The change in length directly relates to the temperature of the specimen. The increases in length at 40 and 49 hours directly coincide with the point of heave initiation and the sudden rise in temperature that accompanies the arrival of warmer water throughout the specimens.

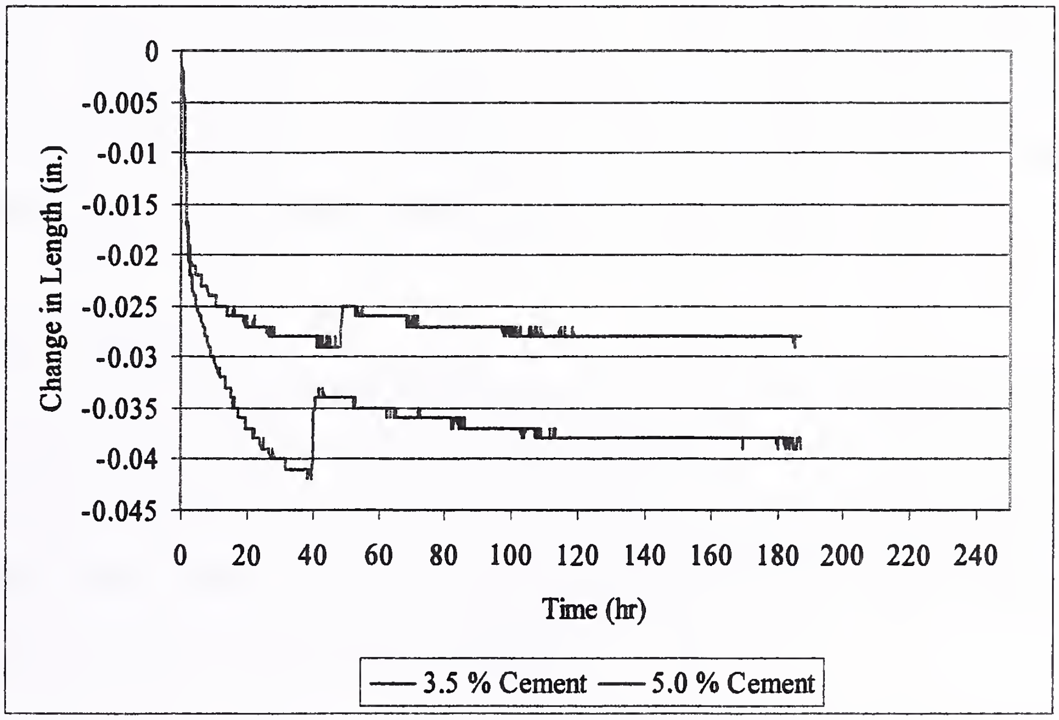


FIGURE 4.13 Height changes for non-frost-susceptible specimens.

CHAPTER 5
CONCLUSION

This chapter outlines the most important findings of the research conducted and gives recommendations on further research.

5.1 Key Findings

The results of the frost heave tests indicate that cement can be a very effective treatment for reducing frost heave and potentially minimizing frost-associated damage to road structures. However, a sufficient amount of cement must be added to problematic soils to achieve acceptable levels of stabilization. As documented in this research, and by Kettle, treatment of frost-susceptible soils with inadequate cement can actually increase frost susceptibility (*12*). The collected data also suggest that, although excessive amounts of cement will control frost susceptibility, a threshold cement content exists, beyond which additional cement only slightly improves the performance of the soil, and increases the likelihood of reflection cracking in the pavement surface. Therefore a window exists where cement can be an effective stabilizing agent if used correctly.

5.2 Recommendations

Further research on the suction characteristics and heaving pressures of the cement treated soil is needed to fully explain the causes of the behavior observed in this research. Further research should also be conducted on the behavior of the material when subjected to a repetitive freeze-thaw regimen. Freeze-thaw testing would more closely approximate the effects of daily and seasonal weather changes.

ACKNOWLEDGEMENTS

The author wishes to thank James Blossom and Susan Sillick of the Montana Department of Transportation for supplying the soil used in this research. Additional thanks is given to Dave Luhr of the Portland Cement Association for his cooperation and the funding that made this research possible. Great thanks, is also given to Dr W. Spencer Guthrie of Brigham Young University for his invaluable guidance and expertise, which truly drove this research.

REFERENCES

1. Henry, K.S., and R.D. Holtz. Geocomposite Capillary Barriers to Reduce Frost Heave in Soils. *Canadian Geotechnical Journal*, Vol. 38, 2001, pp 678–694.

2. Anonymous. A Better Way to Control Frost Heave. Better Roads, Vol. 56, No. 2, February 1986, pp. 42-43.

3. Andersland, O.E. and D.M. Anderson. *Geotechnical Engineering for Cold Regions*. McGraw-Hill New York, 1997 pp. 347-355.

4. Kettle R.J., and E.Y. McCabe. Mechanical Stabilization for the Control of Frost Heave. *Canadian Journal of Civil Engineering*, Vol. 12, 1985, pp. 899-905.

5. Hemstreet, D.A., and T.S. Vinson. Iron(II) Amine Complex Soil Stabilization, *Cold Regions Engineering, Proceedings of the Eighth International Conference on Cold Regions Engineering*, ASCE press, 345 E. 47th Street, New York NY, 1996, pp. 447-458.

6. Brandt, G.H. Chemical Additives to Reduce Frost Heave and Water Accumulation in Soils. In *Highway Research Record*: *Journal of the Transportation Research Board*, No. 393, National Research Council, Washington D.C., 1972, pp 30-44.

7. Ahmad H. Soil Treatment Controls Frost Heave Conditions, *Pipe Line Industry,* Vol. 49, No. 6, Dec 1978, pp. 51-54.

8. Kettle, R. J., and A.T. McNulty. The Resistance of Cement Bount Minestone to Frost Damage, paper No. 54, *Symposium on the Reclamation, Treatment and Utilisation of Coal Mining Wastes*, Durham, England, September 1984.

9. Corr, D.J., P. Monteiro, and J. Bastacky. Observations of Ice Lens Formation and Frost Heave in Young Portland Cement Paste. *Cement and Concrete Research*, Vol. 33, No. 10, 2003, pp. 1531–1537.

10. Sutherland, H.B., and P.N. Gaskin. Factors Affecting the Frost Susceptibility Characteristics of Pulverized Fuel Ash. *Canadian Geotechnical Journal*, Vol. 7, 1970, pp. 69-78.

11. Merril, D.C., and J.M. Hoover. Laboratory Freeze-Thaw Tests of Portland Cement-Treated Granular Bases. In *Highway Research Record*: *Journal of the Transportation Research Board*, No. 255, National Research Council, Washington D.C., 1968, pp 16-29.

12. Kettle, R.J., and R. Williams. Frost Action in Cement-Stabilized Colliery Shale. In *Highway Research Record*: *Journal of the Transportation Research Board*, No. 641, National Research Council, Washington D.C., 1977, pp 41-48.

13. Rosen, W.J., and B.D. Marks. Cold Weather Lime Stabilization. In *Transportation Research Record*: *Journal of the Transportation Research Board*, No. 501, National Research Council, Washington D.C., 1974, pp 35-41.

14. Freitag, D.R., and T. McFadden. *Introduction to Cold Regions Engineering*, ASCE press, 345 East 47th Street, New York, NY, 10017, Chapter 5, page 204, 1997.

15. Konrad, J.M., Soil Freezing Characteristics versus Heat Extraction Rate, DBR paper No. 1257, American Society of Mechanical Engineers Annual Winter Meeting, New Orleans, LA, December 1984.

16. McCarthy, D. F. *Essentials of Soil Mechanics and Foundations*. Prentice Hall, Columbus, 1998.

17. Mitchell, J. K. *Fundamentals of Soil Behavior*, Second Edition. John Wiley & Sons, Inc., New York, 1993.

18. Konrad, J.M., and N.R. Morgenstern. A Mechanistic Theory of Ice Lens Formation in Fine-Grained Soils, *Canadian Geotechnical Journal*, Vol. 17, No. 4, 1980, pp. 473–486.

19. Harris, J.S. *Ground Freezing in Practice*, Thomas Teleford Services Ltd., London, 1995.

20. McGee, David. *The Mechanisms and Effects of Frost Heave* October 15, 1996 http://acad.carleton.edu/curricular/GEOL/classes/geo258/studentswork/McGee.html. Accessed July 2004.

21. Hanks, R.J., and G.L. Ashcroft. *Applied Soil Physics*, Springer-Verlag, New York, New York, 1980.

22. Cary, J.W. A New Method for Calculating Frost Heave Including Solute Effects, *Water Resources Research*, Vol. 23, No. 8, 1987, pp. 1620–1624.

23. Marandi, S.M., I.S. Douglas, and T.W. Cousens. Stress and Temperature Effects on Silt Frost Heave, *Cold Regions Engineering, Proceedings of the Eighth International Conference*, ASCE press, 345 E 47th Street, New York, NY, 1996, pp. 23-34.

24. Konrad, J.M. Frost Susceptibility Related to Soil Index Properties. *Canadian Geotechnical Journal*, Vol. 36, 1999, pp. 403–417.

25. Kaplar, C.W. Phenomenon and Mechanism of Frost Heaving, In *Highway Research Record: Journal of the Transportation Research Board,* No. 304, National Research Council, Washington D.C., 1970, pp. 1-13.

26. Penner, E., The Importance of Freezing Rate in Frost Action in Soils. In *Proceedings of the American Society for Testing Materials*, Vol. 60, 1960, pp. 1151-1165.

27. Hermansson A. *Modeling of Frost Heave and Surface Temperatures in Roads, Doctoral Thesis*, Lulea University of Technology, Lulea Sweden, 2002.

28. Farrington, S.P. Frost Penetration Prediction using Simulation with GIS, http://gis.esri.com/library/userconf/proc02/pap1048/p1048.htm. Accessed July 2005.

29. American Society for Testing and Materials (ASTM) Standards on Disc, CD-ROM, Vol. 04.08, W. Conshohocken, PA, 2005.

30. Scullion, T. and T. Saarenketo. Using Suction and Dielectric Measurements as Performance Indicators for Aggregate Base Materials. In *Transportation Research Record* 1577, TRB, National Research Council, Washington D.C., 1997, pp. 37-44.

31. Guthrie, W. S. and T. Scullion. Assessing Aggregate Strength and Frost Susceptibility Characteristics with the Tube Suction Test. In *Proceedings of the Texas Section, American Society of Civil Engineers, Fall Meeting*, El Paso, Texas, 2000, pp. 197-206.

32. Saarenketo, T., T. Scullion, and P. Kolisoja. Moisture Susceptibility and Electrical Properties of Base Course Aggregates. In *Fifth International Conference on the Bearing Capasity of Roads and Airfields*, Trondheim, Norway, 1998, pp. 1401-1410.

33. Guthrie, W. S., A. Hermansson, and T. Scullion. Determening Aggregate Frost Susceptibility with the Tube Suction Test. *Cold Regions Engineering, Proceedings of the Eleventh International Conference*, May 2002, Anchorage, Alaska.

34. Dirksen, C., and Miller R. D. Closed-System Freezing of Unsaturated Soil, *Soil Science Society of America Journal of Proceedings,* Vol. 30, No. 2, March-April 1966, pp. 168–173.

MEMORANDUM

TO: Susan Sillick, James Blossom
Montana Department of Transportation

FROM: Russell Lay, E.I.T.
Stelling Engineers Inc.

DATE: September 15, 2005

SUBJECT: Sulfate-Bearing Soil

In August of 2004, as I began the research for my M.S. thesis, I made a trip to Helena, Montana, to request that the Montana Department of Transportation donate two barrels of soil for use in the study. The soil was to be included in a research program funded by the Portland Cement Association with the purpose of investigating the potential use of low levels of cement as a soil stabilizer for frost-susceptible soils. Subsequently, in September of 2004 the Montana Department of Transportation graciously sent two barrels of soil to the Brigham Young University Highway Materials Laboratory with the understanding that in return I would share the results of the research conducted on the soil they had sent. One sample was sent from the Bozeman area near Four Corners, along US Highway 84, and another from south of Great Falls near Arrow Creek along US Highway 80.

The purpose of this memo is to report on the testing conducted on the Arrow Creek material. Unfortunately, the soil from Arrow Creek was not able to be included in the study. This memo gives a brief background into the research, a summary of the tests performed on the Arrow Creek material, and reasons why it was unable to be included.

Upon the arrival of the materials, the two soils were air dried and sieved, and hydrometer analyses and Atterberg limit tests were performed to determine the USCS and AASHTO soil classifications of each. The specific gravity of each soil was also measured. The optimum moisture content of each material was established using both the standard and modified Proctor compaction effort. Samples were prepared for unconfined compressive strength tests with varying levels of cement treatment as described in sections 3.1 and 3.2 of the accompanying report.

During the sieving process, several yellow crystals were noticed in the Arrow Creek soil, and the suspicion arose that perhaps they were sulfur. Then, during the 7-day curing period to which the specimens were subjected prior to strength testing, the volume of the cement-treated samples increased dramatically, and the cylinders were too weak to be removed from the fog room without suffering substantial damage. The reasons behind

this dramatic expansion and weakening are twofold. The foremost reason for the expansion and weakening was the formation of ettringite crystals within the soil matrix, which was caused by the reaction of the sulfates within the soil and the calcium within the cement. Secondly, the Arrow Creek material also contains a percentage of expansive clays that, when exposed to the moist conditions of the fog room, further damaged the compacted soil samples.

After learning of the volumetric instability of the cement-treated Arrow Creek soil specimens, Dr. Guthrie suggested that I send a representative sample of the soil to Dr. Pat Harris at the Texas Transportation Institute in order to have its exact sulfate concentration measured. The concentration was found to be approximately 30,000 ppm. This sulfate concentration is ten times greater than the upper limit of 3000 ppm typically used for calcium-based soil stabilizers. Due to the fact that the goal of the research program was to evaluate the effectiveness of using low levels of Portland cement to reduce the frost susceptibility of problematic soils, the decision was made not to include the Arrow Creek material in the study.

A summary of the tests performed on the Arrow Creek material is given in Appendix A.

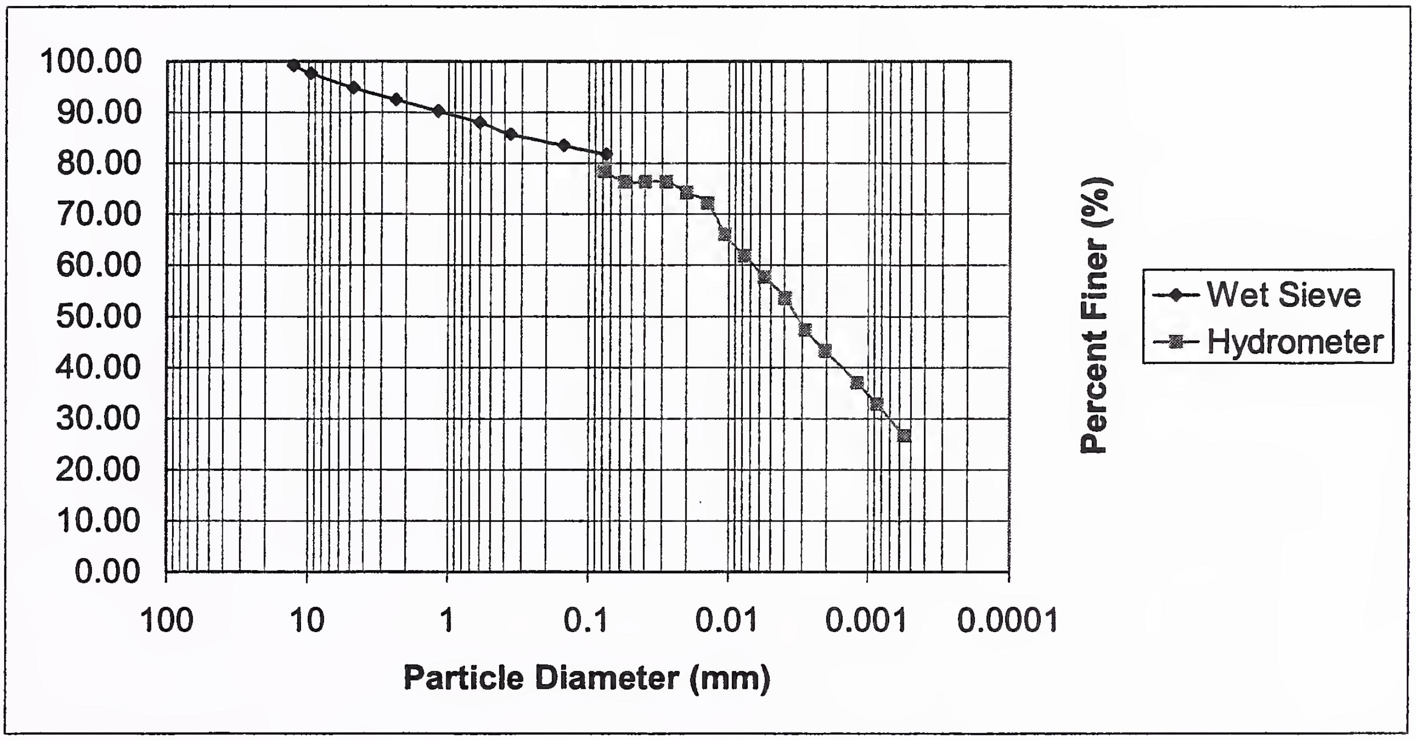
Appendix A

Soil Testing Summary

Material Origin:	Arrow Creek, Montana

USCS classification	CL Sandy lean clay
AASHTO classification	A-7-6 (23)
Army corps of Engineers frost classification	F-3

Particle Size Analysis



Atterberg Limits Summary			
Liquid Limit	=	47.00	%
Plastic Limit	=	19.20	%
Plasticity Index	=	27.80	%

Optimum Moisture Content	
Modified Proctor	12.4%
Standard Proctor	16.7%

Apparent Specific Gravity of Soil Sample 2.73

Appendix B

United States Army Corps of Engineers
Frost Heave Classification Table

Table 3. Corps of Engineers (COE) frost-susceptibility classification.

Frost group	*Soil*	*Percentage finer than 0.02 mm by weight*	*Typical soil types under Unified Soil Classification System*
NFS[*]	(a) Gravel Crushed stone Crushed rock	0–1.5	GW, GP
	(b) Sands	0–3	SW, SP
PFS[†]	(a) Gravel Crushed stone Crushed rock	1.5–3	GW, GP
	(b) Sands	3–10	SW, SP
S1	Gravely soils	3–6	GW, GP, GW-GM, GP-GM
S2	Sandy soils	3–6	SW, SP, SW-SM, SP-SM
F1	Gravely soils	6–10	GM, GW-GM, GP-GM
F2	(a) Gravely soils	10–20	GM, GW-GM, GP-GM
	(b) Sands	6–15	SM, SW-SM, SP-SM
F3	(a) Gravely soils	over 20	GM, GC
	(b) Sands, except very fine silty sands	over 15	SM, SC
	(c) Clays, PI > 12	—	CL, CH
F4	(a) Silts	—	ML, MH
	(b) Very fine silty sands	Over 15	SM
	(c) Clays, PI < 12	—	CL, CL-ML
	(d) Varved clays and other fine-grained, banded sediments	—	CL, ML and SM, CL, CH and ML, CL, CH, ML and SM

[*] Non-frost-susceptible.

[†] Possibly frost-susceptible, requires lab test to determine frost design soil classification.

Appendix C

Correspondence between Myself (Russ Lay), Spencer Gutherie, and Pat Harris
Regarding the sulfate content of the Arrow Creek Soil

1)

Pat:

The Montana DOT donated some "problematic" (that's what we asked for...) subgrade soil for inclusion in my PCA study. It contains some amount of swelling clay, but it may also have gypsum. My student said he found several yellowish crystals that appeared to him to be sulfur. If I mailed some to you, could you measure the sulfate concentration for us? I'm thinking of that simple test you were using when I was still at TTI. If you are agreeable, how much would you need, and to what address should I send it?

Thank you,

Spencer

---

2)

Spencer:

Sure, send it on. I would need about 50 g of air dried soil. Ship it to my attention at CE/TTI Bldg, rm 607C, 405 Spence, TAMU 3135, College Station, TX 77843-3135.

Pat Harris
Associate Research Scientist
Texas Transportation Institute
phone: (979) 845-5845

---

3)

Russ:

Could you please prepare the soil sample for Pat. Let's send him 100 g so he has extra.

S. Guthrie

(4)

Pat:

I'm just writing to find out if my sample arrived at TTI yet. My student is anxious to find out if we have to worry about sulfate or not...

Thanks!

Spencer

---

(5)

Spencer:

I finished testing your sample from Montana. I crushed the sample with a mortar and pestle and passed it through a # 40 sieve. I then separated out three 5g lots and diluted each with 100g double distilled water. Each sample was shaken on our shaker for a period of one minute and then conductivity was measured. Following conductivity measurements each sample was filtered with Fisher P5 filter paper and the filtrate was measured with the colorimeter for the actual sulfate concentration in ppm. All measurements were conducted at 22ºC.

You definitely have a sulfate problem if this sample is representative of the entire soil. The concentration is approximately 30,000 ppm in this particular sample. I have attached the results.

Sincerely,

Pat Harris
Associate Research Scientist
Texas Transportation Institute
phone: (979) 845-5845

---

(6)

From: W. Spencer Guthrie
To: rdl22@email.byu.edu
Cc:
Bcc: Russell Lay
Date: 03/02/05 05:54 pm
Subject: FW: Soil Sample
Attachments: Spencer.xls (23KB)

Well, now we can call Jim Blossom...This is a VERY high concentration of sulfates. A common maximum threshold value for using calcium-based stabilizers is just 3,000 ppm.